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STUDIES OF THE QUALITY AND COST-EFFECTIVENESS OF A NOVEL CONCEPT OF OPEN-DIE FORGED POWERPLANT MAIN SHAFT

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An innovatory concept of open-die forging of windmill main shaft is described. Comparative study of the new technology based on the concept of cogging hollow shaft on mandrel featuring material savings and higher quality of a finished part versus traditional production chain of this component is presented, indicating benefits and technological setbacks of industrial implementation. Results of industrial sampling aided with numerical simulation form guidelines for technological realization.

Key words: open-die forging, cogging on mandrel, wind turbine, low-speed shaft

INTRODUCTION

High costs of the renewable energy call for reducing manufacturing costs of both energy and installations involved. In this respect, material and energy savings are sought for, to optimize the total manufacturing costs. In the light of predicted increase in the number of windmill power-plant installations within this decade, according to the current EU environmental policy, one of the emerging innovations is a windmill shaft with net-forged central orifice [1]. The main shaft (low speed shaft), is a basic element of a wind turbine. As it connects the generator and the rotor hub (Figure 1), severe service conditions of cyclic loading impose high quality requirements on this member. Thus, it is manufactured with incremental forging process, composed of open-die forging and subsequent machining (Figure 2), which is a noncompetitive technology for such parts.

The shaft shaped by cogging on mandrel becomes a real alternative to traditional forging and machining. In order to reduce the material costs a novel concept of the shaft has been proposed. The novelty depends on producing as-forged central hole with forging operations, reducing machining allowances. For this reason, the notion “net-forging” is used here in reference to open-die forging. Changes in forging technology in the aftermath of reduced ingot and different manner of processing in consecutive shaping operations is summarized in Figure 3. Although similar efforts have been found these days, e.g. generator turbines [2, 3], it has never been used in production of long shafts.

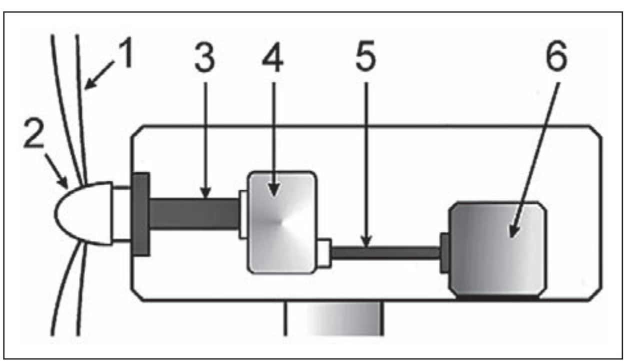

Figure 1 Functional scheme of a wind turbine: 1 – blade, 2 – hub, 3 – main shaft, 4 – gearbox, 5 – high speed shaft, 6 – generator

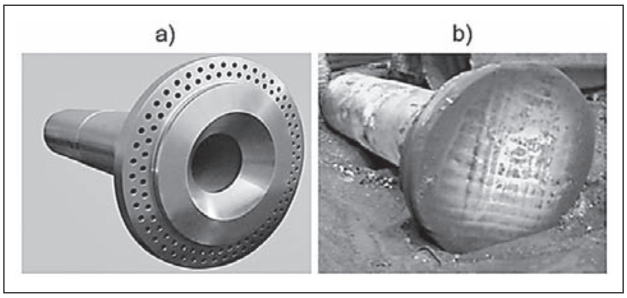

Figure 2 Wind turbine main shaft: a) final product, b) forged part

The reduced mass of the finished part allows the use of smaller ingot, however, producing hollow shape necessitates changes in technology, which influence gain-costs balance. This work summarizes pros and cons of the new concept of the shaft and the new technology.

Plan and methods of the study

Considering the new concept of manufacturing the power-plant main shaft, which involves near-net forged central orifice as a competition versus solid shaft with machined orifice, two aspects are addressed: design of the new technology and its correctness, and an estimation of cost-effectiveness to evaluate its economical reasonability.

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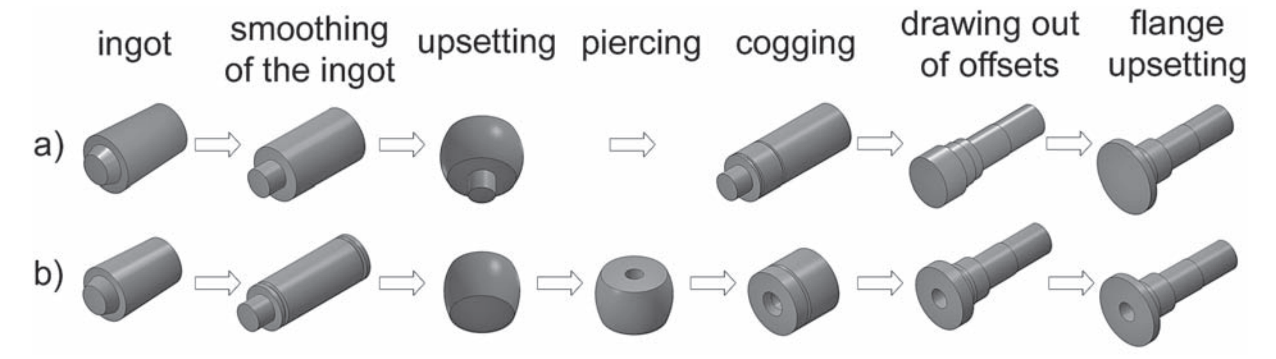


Figure 3 Forging technology of windmill main shaft: a) solid part, b) hollow part

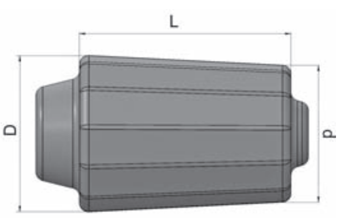
The comparison takes into consideration factors such as: material waste, energy consumption, machining time, as well as, technological aspects of the forging technology, including feasibility of the new forging technology and quality of the forging. The comparative study is based on the measurement of times of individual operations during experimental sampling and numerical modeling with Finite Element Method (FEM), the carried out quality assessment based on calculation of some of the indicators, such as strain distribution, forging yield, load or temperature distribution on heating. FEM modeling was conducted with commercial code QForm3D, with the use of thermo-mechanical coupled simulation, with boundary conditions for FEM simulations, as well as data on times of machining, taken from industrial conditions [4].

COMPARATIVE ANALYSIS OF THE TECHNOLOGIES

Material savings

Producing the central orifice with plastic forming brings significant increase in the forging yield. Instead of removing the core portion of the elongated ingot, the volume of metal is displaced during punching to form future walls of the shaft. The volume of the orifice brings serious material savings, resulting in use of 40 Mg ingot instead of 50 Mg. As the dimensions of an ingot (Table 1) are related to the times of heating, with use of smaller ingot, less energy consumption is expected.

Table 1 **Dimensions of the ingots**

	40 tons (Q40)	50 tons (Q50)
The 1st end diameter / D	1,63 m	1,76 m
The 2nd end diameter / d	1,41 m	1,51 m
Corpus length / L	2,27 m	2,43 m
Corpus volume / V_c	5,21 m^3	4,19 m^3
Total volume / V	5,83 m^3	4,67 m^3

Heating and reheating times

Before forging, the ingot of Cr-Ni-Mo steel is heated up in a gas furnace. Large diameter and temperature gradients, inducing excessive stresses, call for quadruple heating sequence with equalizing holds. To save the energy, the ingot is transferred in hot condition and reheated prior to forging. In reheating from 700 °C on the surface, as measured in the plant, it takes about 5 hours to achieve forging temperature. However, temperature in the axis is then only 850 °C (Figure 3a). Until forging point is reached, the surface zone is exposed to the detrimental effect of high temperature. Employing ingot Q40 allows shortening of the reheating time, which takes four hours longer for ingot Q50 – Figure 4.

In industrial practice, both of the ingots need one more intermediate reheating during forging. Not only does it make the bigger ingot less economical, but it also deteriorates its quality, as reheating can lead to excessive scale formation, deoxidation and grain growth during in-between forging re-heating stages.

Strain analysis during open-die forging

The quality of the part depends a lot on strain uniformity. Satisfactory uniformity of strain can only be obtained with use of large unit reductions and large values of the relative feed ratio. Both of them cause the forging load rise. Therefore, if the final diameter is too large to use

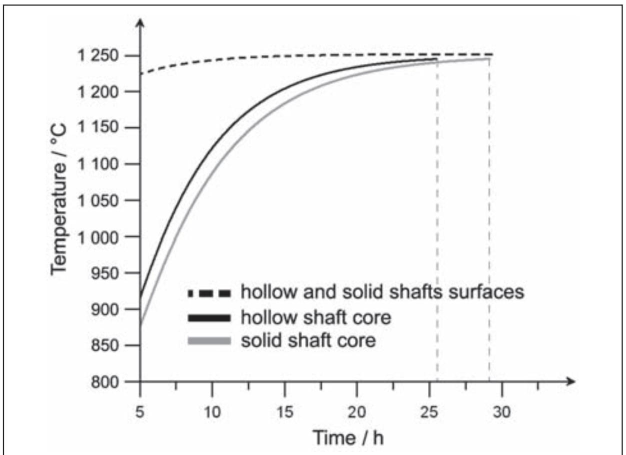


Figure 4 Temperature evolution during heating up the considered ingots

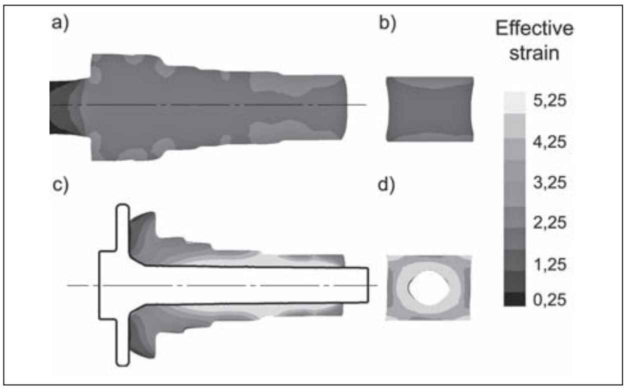


Figure 5 Effective strain distribution: a, b) solid shaft, c, d) hollow shaft; a, c) longitudinal and b, d) transverse

large bites, it is realized with more passes or lower unit deformation. It very often does not penetrate into the core of the ingot, where axial porosities prevail [3, 5]. If insufficiently pre-worked, they may stress concentrators on the inner surface as after drilling the central hole they will locate at the inner surface. In hollow forged shaft, thinner sections are shaped by forging, which enables closing the voids, minimizing the hazard of surface cracks.

The analysis of effective strain distribution on the cross sections shows that in the case of solid shaft its average is 3,5, while in the case of hollow shaft, it reaches about 4,3 (Figure 5). In both cases, nonuniformity of strain, natural for the cogging process, can be observed (Figure 6). However, in the hollow part the gradient is opposite to the solid shaft – the highest values of effective strain are observed on the inner surface, which improves the quality and toughness.

For quantitative analysis, plots of measured values of effective strain were compared in the surface and core zones. The plots of effective strain on the length confirm progression of its level with decreasing diameter in consecutive sections, which is valid for the hollow shaft shaped through cogging. For the hollow shaft it is much more distinct. In the solid shaft, the strain level exhibits uniformity, however the level of the effective strain hardly exceeds 2, both in the surface and the axis. The region of the main diameter is the only exception.

Semi open-die forging analysis

The flange is the most demanding element of the part to be forged. Due to large diameter and uniform strain requirements, it can only be shaped through upsetting the preformed end. When cogging is complete the, manipulating hub is cut off and the semi-finished part is turned into vertical position to a special set of tools to be upset-forged in a die-impression (Figures 7 a, b). Due to load restrictions, it is realized in a sequence of about 20 blows, as described elsewhere [4]. This technology works properly for a solid shaft. Unfortunately, making a “net-shape” geometry in the early stages of forging leads to its deformation and distortion during one of the last operations in the production chain – the upsetting of the flange (Figure 8). It significantly impedes the machining and so far it is a serious setback.

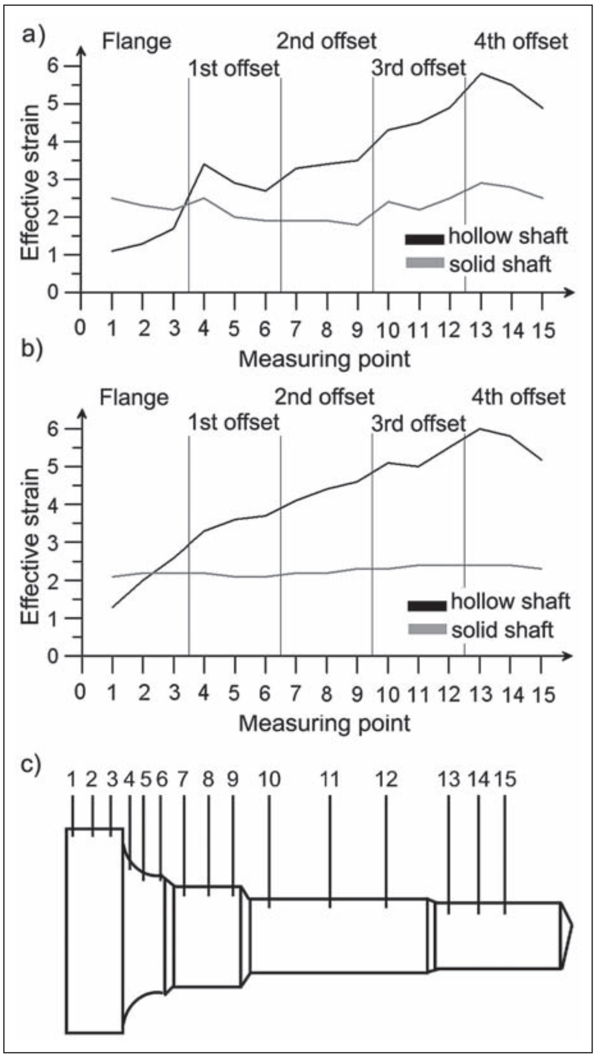


Figure 6 Effective strain on a crosscut: a) surface, b) ½ of radius, c) points location

Machining times

Machining, the most crucial stage in the production chain, can be divided into preliminary and final machining (Table 2). The first stage is preparation for the initial ultrasonic testing, and for extension of the central orifice. The final machining provides the shaft with final dimensions and surface quality. As shown in Table 2, pre-machining time is longer for the hollow shaft, in the aftermath of distortion of the slot during semi-open die-upsetting operation. The rest remains unaffected.

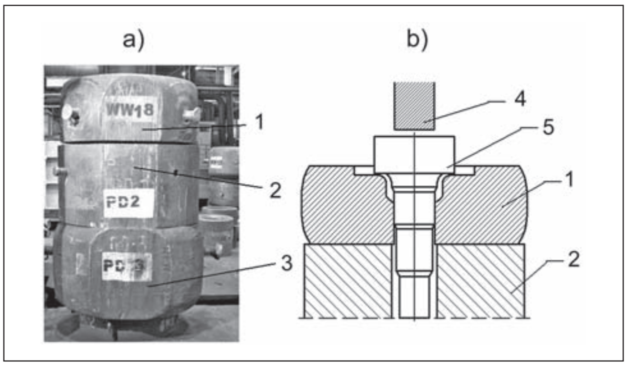


Figure 7 Upsetting of the flange, where: 1 – the die, 2,3 – distance rings, 4 – flat narrow die, 5 – forging

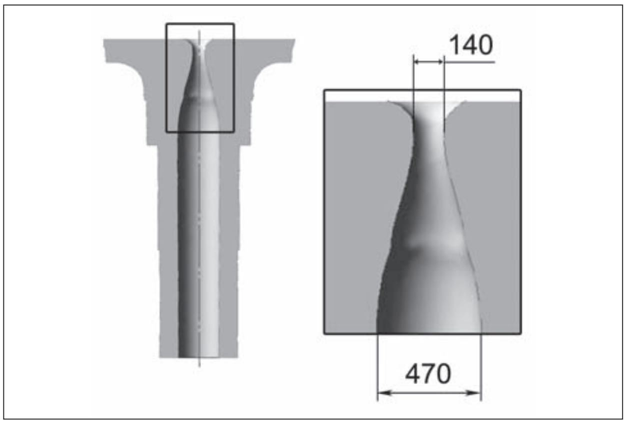


Figure 8 The central orifice distortion during shaping of flange in the hollow shaft

Table 2 **Times of machining operations**

No	Name of operation	Time / h	
		solid	hollow
1.	Preparation	2,2	11,5
2.	Pre-machining	80,0	170,0
3.	Drilling the orifice	8,0	-
(after heat treatment)			
4.	Preparing for enlargement	50,0	50,0
5.	Enlargement of the orifice	12	12
6.	Final machining	48,0	48,0
	Total machining time	200,2	291,5

SUMMARY

The described method of manufacturing power windmill main shaft, related to the new concept of the part involves modified forging process, resulting in "net-shape" forged central orifice obtained through waste-free forging stages with limited amount of machining. The two technological chains were compared in terms of the weight of the forging ingot, heat-up times, forging allowances on the final part, time and complexity of the forging process, and effective strain distribution in the forged part, as summarized in Table 3.

Heating time of forging ingot in forging the hollow shaft is significantly shorter due to lower weight of the ingot. However, as the smaller sections chill faster, more re-heating operations makes the total time of heating operations longer, as compared to the solid shaft.

Table 3 **Pros and cons of the new technology**

	Hollow	Solid
Smaller ingot	+	
Shorter ingot heating-up time	+	
Shorter total re-heating time		+
Shorter forging time		+
Favourable strain distribution	+	
Less number of forging tools		+
Reduced flange-shaping time	+	
Higher forging yield	+	
Lower forging load	+	
Shorter total machining time		+
Higher machining yield	+	
Higher total yield	+	

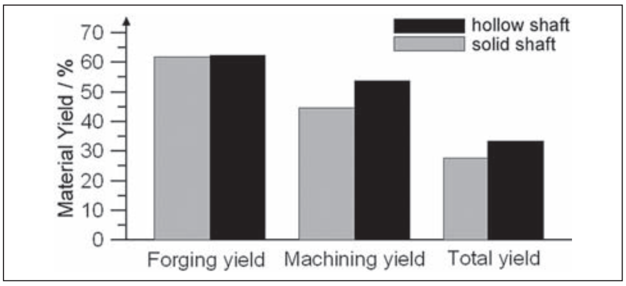


Figure 9 Comparison of the material yield

The total time of press exploitation in the case of hollow shaft forging is about 25 % longer than that measured for the solid shaft.

An important factor that contributes to the total manufacturing cost is forging yield, which is defined as the ratio of the weight of the final part to the weight of the ingot. Forging yield amounts to 61,9 % for the solid shaft, compared to 62,5 %, referring to 20 % smaller ingot, for the hollow shaft (Figure 9). Similarly, machining yield can be determined. The values of this parameter are 44,8 % (solid shaft) and respectively, 53,7 % (hollow shaft), more beneficial in terms of machining yield.

CONCLUSIONS

The comparison presented in the study indicates that the new technology is more cost-effective, as it offers several benefits, mainly, lower material waste, which accounts for longer machining time.

Forging process for shaping the hollow shaft is more complex and calls for auxiliary tools. However, significant material savings and significantly higher level of accumulated strain, as well as its distribution on the length of the shaft, speaks for the "net-shape" hollow preform, as it offers better quality of the final product. Strain level in the core area of the shaft, which is bound to improve the quality and soundness of the inner surface of the shaft is of particular importance. Despite the net-shape accomplishment, the total machining time of the hollow shaft is longer, on account of distortion of the finish-forged central orifice, however, this problem could be easily resolved.

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Note: The responsible professional translator for English language is Karolina Cheppe, English Language Group, SJO AGH, Kraków